Methodology for Calculating and Redefining Cold and Hot Start Emissions

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In recent years, the emission control technology used with motor vehicles has developed such that running exhaust emissions have been reduced significantly, making the contribution of emissions due to start-up procedures a large portion of the emission inventory. The present method of calculating start emissions involves all three bags of the Federal Test Procedure. However, problems with this methodology make it necessary to redefine how start emissions are characterized in the inventory. This memorandum presents a new methodology to calculate start emissions for all passenger cars, light-duty trucks, and medium-duty trucks.

Two test programs were designed to evaluate start emissions as a function of engine-off, or soak time, and to calculate start emissions independent of trip distance. The two programs were combined for a total of 29 vehicles consisting of various catalyst configurations, fuel delivery systems, and cylinder sizes. Modal, second by second, emissions data were recorded while testing the vehicles after varying periods of soak time. Analysis of the data showed that start emissions can be represented as a continuous function of soak time. Using a common base of trip activity data, the impact of the new methodology on the emission inventory was assessed. The methodology outlined in this memorandum will be incorporated into the latest version of the motor vehicle emission inventory model, EMFAC 7G.

INTRODUCTION

Background on Current Methodology

Currently, emissions data are collected by testing vehicles over the Federal Test Procedure (FTP). The FTP is a driving cycle of approximately 11.0 miles in length with an average speed of 19.6 miles per hour. During the test, the vehicle is exercised over a series of accelerations, decelerations, idles, and cruises designed to simulate a typical trip in an urban area. The cycle consists of three parts: cold start (bag 1), stabilized or running portion (bag 2), and hot start (bag 3). The emissions associated with the start and warm-up of a vehicle are currently defined as "incremental increases" to running emissions which are assumed to occur at all times (Figure 1).

Numerically, incremental start emissions are defined as the difference in emissions between bag 1 and bag 2 (speed corrected) for cold starts, and between bag 3 and bag 2 (speed corrected) for hot starts. Although applied to all trips as instantaneous increments, this methodology implies that both cold and hot starts occur over the first 3.59 miles of a trip at an average speed of 25.6 miles per hour (the distance and speed of bags 1 and 3). For modeling purposes, a cold start is defined as a start which occurs one hour or more after the engine has been turned off for a catalyst-equipped vehicle, and after four hours or more for a non-catalyst vehicle. A hot start is defined as a start which occurs before one hour of soak for a catalyst-equipped vehicle, and before four hours for a non-catalyst vehicle.

Inadequacies of the Current Methodology

Staff believe that the current methodology is inadequate for modeling short trips in that 3.59 miles of start emissions are attributed to all trips regardless of length. Although bag 2 is speed-corrected to the same speed as bag 1, subtracting the two implies that speed is the only difference between the two bags. It does not account for the fact that the two bags are different with respect to driving time and various transient events. Furthermore, "warm starts", starts occurring between soak periods of 10 to 60 minutes, are not defined.

Due to the changes in the speed correction factors for EMFAC 7F, estimated running emissions have increased substantially. At the same time, hot start incrementals decreased in value because of improved emission controls. For these reasons, the current methodology occasionally produces negative values for hot start incrementals, reflecting the small differences in the amount of emissions produced between the running portion and the hot start portion of the FTP (Figure 2). Given the short comings of the current model, the definition of a cold and hot start must be reviewed.

The test programs were designed to evaluate start emissions as a function of variable engine-off times, engine cranking, various driving modes, and/or catalyst light-off and cool-down time. Distinguishing "crank" emissions due to the start of an engine would eliminate negative incrementals produced by the current method.

TEST PROGRAM

A total of 29 vehicles were tested for these projects. The test fleet consisted of vehicles with various engine sizes and catalyst configurations. These configurations included non-catalyst, catalyst-equipped, warm-up catalyst-equipped, and one prototype vehicle equipped with an electrically heated catalyst (EHC). The EHC vehicle was important in modeling low emission vehicles in the fleet. For this analysis, it was assumed that the EHC would be heated for 40 seconds and the air injection would be on for 75 seconds for all soak periods 60 minutes and greater. While 29 vehicles were tested in all, 3 were excluded from the final analyses due to questionable data and results. Table 1 gives the breakdown of the vehicles.

In addition to the FTP and bag 1 without a soak, the vehicles of the first program were tested over a special "start test cycle", driven after varying periods of soak. The cycle consisted of 10 seconds of idle, an acceleration of 3.3 mph/sec, a cruise of 35 mph for 435 seconds, a deceleration of 3.3 mph/sec, and another 40 seconds of idle. Figure 3 shows the speed versus time trace. This cycle was constructed so that start emissions can be analyzed independent of transient events (hard accelerations and decelerations). An acceleration of 3.3 mph/sec and a speed of 35 mph were incorporated into the cycle to obtain enough flow of exhaust gases needed to be measured by the constant volume sampling (CVS) unit. While the cycle is not equal in miles, 4.4 vs. 3.59 miles, the time period was set at 505 seconds to make it comparable to bags 1 and 3 of the FTP. The vehicles were driven over this cycle after the following periods of soak (in minutes): overnight (minimum of 720 minutes or 12 hours), 120, 60, 50, 40, 30, 20, 10, 5 and no soak.

Vehicles of the second program were tested over both the FTP and the Unified Cycle (UC). They were also tested after varying periods of soak; however, bag 1 of the UC was used instead of the special start cycle. While the special start cycle in the first program was designed to isolate start emissions independent of transient events, the UC was used in the second round to represent a more contemporary account of driving events occurring during start-up procedures. Figure 4 shows the speed vs. time trace of the Unified Cycle. Analysis of the first set of vehicles illustrated a need for soak times between 120 and 720 minutes. For this reason, the vehicles from the second program were driven over the following periods of soak (in minutes): overnight (minimum of 720 minutes or 12 hours), 360, 300, 240, 180, 120, 90, 60, 50, 40, 30, 20, 10, and no soak.

For both programs, modal exhaust hydrocarbon (HC), carbon monoxide (CO), oxides of nitrogen (NOx), and carbon dioxide (CO_2) emissions data, as well as second by second catalyst temperature were recorded for all tests.

Table 1. Vehicle information for Start Emissions Testing

(a) First Data Set

Veh #	Year	Manufacturer and Model	# Cyl	Cat Type	Fuel Sys
1	1971	GM BUICK LE SABRE	8	NONE	CARB
2	1972	VOLVO	4	NONE	PFI
3	1985	CHRYSLER FIFTH AVENUE	8	TWC	CARB
4	1970	GM CHEVROLET MALIBU	8	NONE	CARB
5	1972	VOLKSWAGEN BUG	4	NONE	CARB
6	1993	TOYOTA COROLLA	4	TWC (WU)	PFI
7	1992	TOYOTA LEXUS LS400	6	TWC (WU)	PFI
8	1993	FORD THUNDERBIRD	8	TWC (WU)	PFI
9	1993	TOYOTA CAMRY LE	4	TWC (WU)	PFI
10	1991	NISSAN SENTRA	4	TWC	PFI
11	1990	TOYOTA COROLLA	4	TWC	PFI
12	1990	GM BUICK LE SABRE	6	TWC (EHC)	PFI

(b) Second Data Set

VEH #	Year	Manufacturer and Model	# Cyl	Cat Type	Fuel System
13	1991	TOYOTA CAMRY	4	TWC (WU)	PFI
14	1992	HONDA ACCORD	4	TWC	PFI
15	1986	VOLKSWAGEN JETTA	4	TWC	PFI
16	1988	HONDA CIVIC	4	TWC	PFI
17	1989	DODGE DYNASTY	6	TWC	PFI
~~18~~	~~1983~~	~~FORD THUNDERBIRD~~	~~6~~	~~TWC~~	~~CARB~~
19	1992	FORD TEMPO	4	TWC	PFI
20	1987	HYUNDAI EXCEL	4	TWC	CARB
21	1986	TOYOTA VAN (LDT)	4	TWC	PFI
22	1992	FORD TAURUS	6	TWC	PFI
23	1992	PONTIAC GRAND AM	4	TWC	PFI
24	1992	CHEVROLET LUMINA	6	TWC	PFI
25	1992	CHEVROLET ASTROVAN	6	TWC	TBI
26	1985	CADILLAC EL DORADO	8	TWC	TBI
27	1988	CHRYS DODGE DYNASTY	6	TWC	PFI
~~28~~	~~1985~~	~~MITS DODGE COLTE~~	~~4~~	~~TWC CL~~	~~CARB~~
~~29~~	~~1989~~	~~TOYOTA COROLLA~~	~~4~~	~~TWC CL~~	~~CARB~~

* TWC - Three-way Catalyst
WU - Warm-up Catalyst
EHC - Electrically Heated Catalyst

CARB - Carbureted
TBI - Throttle-Body Fuel Injection
PFI - Port Fuel Injected

** Vehicles excluded from final analyses

METHODOLOGY

The methodology to calculate and redefine start emissions for all passenger cars, light-duty trucks, and medium-duty trucks is composed of the following:

1. Calculate start emissions expressed in grams per soak time, independent of 3.59 miles of trip length
2. Establish start emissions as a continuous function of soak time
3. Develop a correction factor to adjust the FTP based basic emission rates

Start Emissions Independent of Trip Length

One goal of the new methodology is to calculate start emissions in grams rather than grams per mile, making it independent of 3.59 miles of trip length. For each vehicle/pollutant combination, cumulative emissions data were plotted for all soaks. As an example, a plot of cumulative HC emissions versus time for vehicle 12 is shown in Figure 5. The point of inflection, or plateau, of each curve indicates the time at which the emissions stabilize for the individual soaks. After this point, the start event is over and the vehicle is assumed to be producing only running emissions. Investigation of the modal emissions data used in the analyses for all vehicles showed that all of the emissions attributable to the start of the vehicle occurred within the first 100 seconds after start-up procedures, regardless of vehicle technology type. For this reason, the start interval was defined as 100 seconds for all pollutants and vehicles.

The difference between the cumulative emissions and the cumulative running emissions (estimated from the no soak test) for this interval resulted in start emissions expressed in grams per soak time. Hence, the amount of start emissions for each vehicle/pollutant/soak combination can be expressed by the following equation:

$$z_i = CE_i - RE \qquad (1)$$

where z_i = start emissions in grams for soak time *i*,
CE_i = cumulative emissions produced during the start interval for soak time *i*,
RE = cumulative running emissions produced by the vehicle during the start interval.

The start interval is defined as 100 seconds.

Table 2 gives the average grams per start produced by the individual soaks of each vehicle class.

Table 2. Average Start Emissions (g)

(a) Non-catalyst vehicles

Soak	HC	CO	NOx	CO2
Overnight	4.2841	48.8549	0.5259	136.4219
120 min	2.6388	12.5811	0.9758	123.2506
60 min	2.1631	4.1480	1.0210	98.1335
50 min	2.0701	4.3596	0.8961	85.9819
40 min	2.1923	9.5849	0.6128	70.4107
30 min	1.1739	3.6832	0.8576	63.5574
20 min	1.3344	8.6480	0.7951	65.8068
10 min	1.5924	17.4785	0.5171	45.0740
5 min	2.0167	16.2938	0.5896	46.3194

(b) Catalyst-equipped vehicles

Soak	HC	CO	NOx	CO2
Overnight	2.4661	22.8633	0.9253	78.2489
360 min	1.5319	16.6241	0.6989	41.7070
300 min	1.5576	15.0106	0.7156	43.6469
240 min	1.3514	16.4110	0.8094	34.4298
180 min	1.4344	15.2948	0.8063	29.1808
120 min	1.3952	14.4279	1.0314	39.8401
90 min	1.2124	14.6436	0.7130	21.8906
60 min	1.0559	9.7590	1.0050	24.0809
50 min	1.0325	10.4581	0.8665	18.2308
40 min	0.9051	8.9614	0.7944	13.9631
30 min	0.7284	6.0189	0.6907	10.8831
20 min	0.5018	5.8415	0.5247	10.5124
10 min	0.2456	3.3323	0.2849	9.5992
5 min	0.0705	1.3782	0.1816	5.0415

(c) Electrically-heated catalyst equipped vehicles

Soak	HC	CO	NOx	CO2
Overnight	1.1120	4.1816	1.3223	103.8468
120 min	0.6546	2.6111	1.8357	44.3524
60 min	0.3889	2.2586	1.8300	25.8197
50 min	0.3926	2.0720	1.7705	5.3795
40 min	0.3280	1.6554	1.7209	4.6862
30 min	0.1668	0.3907	1.5958	12.2840
20 min	0.0481	0.1168	1.8297	5.5927
10 min	0.0221	0.0566	1.4388	6.6891
5 min	0.0246	0.1758	1.8003	1.8975

Start Emissions as a Continuous Function of Soak Time

Once the total grams per start calculations were completed for all soak times for a particular vehicle, the start emissions for various soaks were normalized to the overnight soak. This allowed all other soaks to be expressed as a function of start emissions following the overnight soak. An average of all normalized emissions for each soak time was taken for all catalyst and non-catalyst vehicles. Table 3 shows the resulting normalized factors for all vehicle groups. For catalyst-equipped vehicles in Table 3(b), start emissions between overnight and 120 minute soaks decreased by at approximately 40, 25, and 50 percent for HC, CO, and CO_2 respectively, and increased by 15 percent for NOx. Similar trends also occurred for the non-catalyst and EHC vehicles.

Two separate "best fit" curves on the average normalized emissions data were used to describe the soak functions. The normalized curves for the four pollutants of non-catalyst, catalyst-equipped, and the electrically heated catalyst equipped vehicles are shown in Figures 6, 7 and 8. The curves are represented by the following polynomial equation:

$$\text{Normalized Start Emissions of HC, CO, NOx, and } CO_2 = a_0 + a_1 * t + a_2 * t^2 \qquad (2)$$

where t = soak time (minutes),
a_i = coefficients of the curves,
Normalized start emissions = grams per soak time *i* divided by grams per overnight soak.

The corresponding coefficients and soak time intervals for each vehicle class are given in Table 4. By using the above continuous functions in conjunction with the start emissions produced following a cold soak, it is possible to estimate the amount of start emissions produced after any soak time.

Figures 6, 7 and 8 illustrate the trend of start emissions as the duration of the soak changes from an overnight (720 minutes) to any other time intervals. Using the current definition of a cold start for a catalyst-equipped vehicle, a soak time of 60 minutes should produce the same amount of start emissions as an overnight soak. However, the analysis performed on the vehicles tested at different soak time intervals reveal a noticeable difference in emissions between the overnight and 60 minutes soaks. The illustration for the catalyst-equipped vehicles in Figure 7 shows the overnight soak produced more HC, CO and CO_2 and less NOx emissions than the other "cold" tests, and suggests that even after 60 minutes the car is still warm and the catalyst is still partially efficient in reducing start HC and CO emissions. Thus, a cold start as defined by a soak time of one hour or more for a catalyst-equipped vehicle appears to be inadequate and would tend to overestimate HC, CO, and CO_2 emissions and underestimate NOx emissions. Similarly, a hot start as defined by a soak time of less than one hour and represented only by 10 minutes of soak (per current EMFAC) would tend to underestimate HC, CO, NOx and CO_2 emissions for soak times greater than 10 minutes and less than 60 minutes.

Table 3. Average Normalized Emissions (g)

(a) Non-catalyst vehicles

Soak	HC	CO	NOx	CO2
Overnight	1	1	1	1
120 min	0.5274	0.2479	2.4211	0.9922
60 min	0.4858	0.0888	2.4602	0.8219
50 min	0.4756	0.1242	2.2616	0.7212
40 min	0.5309	0.2317	1.0383	0.5709
30 min	0.3390	0.1226	2.2178	0.3820
20 min	0.3078	0.1900	1.9694	0.5701
10 min	0.3618	0.4311	1.5112	0.4352
5 min	0.4176	0.3760	1.3775	0.4320

(b) Catalyst-equipped vehicles

Soak	HC	CO	NOx	CO2
Overnight	1	1	1	1
360 min	0.7857	0.8482	0.9941	0.6776
300 min	0.7902	0.7853	1.1319	0.7196
240 min	0.7188	0.7948	1.1800	0.4981
180 min	0.7387	0.8068	1.1841	0.5281
120 min	0.6233	0.7422	1.1563	0.5137
90 min	0.6391	0.7248	1.0594	0.3184
60 min	0.4893	0.4849	1.1192	0.2655
50 min	0.4902	0.4768	1.0109	0.2030
40 min	0.4314	0.4216	0.9525	0.1454
30 min	0.3430	0.2978	0.8761	0.1456
20 min	0.2336	0.2466	0.6500	0.1130
10 min	0.1268	0.1605	0.3940	0.1115
5 min	0.0275	0.0769	0.2280	0.0551

(c) Electrically-heated catalyst equipped vehicles

Soak	HC	CO	NOx	CO2
Overnight	1	1	1	1
120 min	0.5887	0.6244	1.3882	0.4271
60 min	0.3498	0.5401	1.3839	0.2486
50 min	0.2941	0.3371	1.1699	0.0775
40 min	0.2458	0.2693	1.1371	0.0675
30 min	0.1250	0.0636	1.0544	0.1770
20 min	0.0361	0.0190	1.2090	0.0806
10 min	0.0165	0.0092	0.9507	0.0964
5 min	0.0184	0.0286	1.1895	0.0273

Table 4. Coefficients of the Normalized Emission Curves

(a) Non-catalyst vehicles

	HC curve 1	HC curve 2	CO curve 1	CO curve 2	NOx curve 1	NOx curve 2	CO2 curve 1	CO2 curve 2
a0	0.3806708	0.4362844	0.4380312	-0.085415	1.31568216	2.48061071	0.36302129	0.99064304
a1	-0.001638	0.0007826	-0.00998	0.0030314	0.0275196	-0.0001841	0.00697116	1.2996E-05
a2	6.642E-05		7.019E-05	-2.12E-06	-0.0001531	-2.6E-06	-1.335E-05	
domain (min)	0-52	53-720	0-119	120-720	0-119	120-720	0-115	116-720

(b) Catalyst-equipped vehicles

	HC curve 1	HC curve 2	CO curve 1	CO curve 2	NOx curve 1	NOx curve 2	CO2 curve 1	CO2 curve 2
a0	0	0.5713026	0	0.7064116	0.11796024	1.12983289	0	0.25889542
a1	0.012723	0.0007196	0.0119476	0.0003344	0.02966956	2.2138E-05	0.00433672	0.0014848
a2	-6.3E-05	-1.76E-07	-4.76E-05	1.001E-07	-0.000215	-3.04E-07	-2.393E-06	-6.364E-07
domain (min)	0-89	90-720	0-116	117-720	0-61	62-720	0-96	97-720

(c) Electrically-heated catalyst equipped vehicle

	HC curve 1	HC curve 2	CO curve 1	CO curve 2	NOx curve 1	NOx curve 2	CO2 curve 1	CO2 curve 2
a0	0	0.5064134	0	0.4473331	1.05016953	1.37178406	0.0537617	0.31251366
a1	0.0056083	0.0006855	0.0070714	0.0016176	0.00361983	0.00026788	0.00114395	0.00095484
a2	-5.09E-06		-1.33E-05	-1.18E-06	-5.575E-06	-1.089E-06	1.6526E-05	
domain (min)	0-117	118-720	0-107	108-720	0-113	114-720	0-119	120-720

Adjustment to the Basic Emission Rates

Adjustments to the basic FTP based bag 1 emission rates used in EMFAC are needed in order to model start emissions for real-world conditions that are not accounted for in the current methodology. Ideally, the new methodology requires that start emissions be measured using a "start cycle" representative of real-world driving patterns immediately following start-up procedures. A representative cycle which captures the events occurring before the catalyst is fully warmed has not yet been developed. As a result, a Start Correction Factor (StF) was derived to adjust the basic emission rate of bag 1 of the FTP such that these conditions are reflected. Numerically, the Start Correction Factor is defined as follows:

$$\text{StF} = \frac{\text{CE}_{100}\text{ UC bag 1 (g)}}{\text{FTP bag 1 (g/mi)}} \tag{3}$$

where StF = Start Correction Factor,
CE_{100} UC bag 1 = cumulative emissions within the first 100 seconds of bag 1 of the Unified Cycle (g),
FTP bag 1 = bag 1 emissions of the FTP cycle (g/mi).

The factor will adjust the basic emission rate to reflect real word driving events by incorporating bag 1 of the Unified Cycle (UC) as shown in equation (3). The current methodology assumes that the FTP cycle is representative of current in-use driving patterns. However, recent studies have established that the UC represents a more contemporary account of typical driving events. The FTP driving cycle was developed over 20 years ago and was modified to reflect the limitations of the dynamometers used at that time. The UC was recently developed in an attempt to more accurately represent real-world driving patterns and motor vehicle emissions. The cycle was based on data gathered using an instrumented chase car in the greater Los Angeles area. It contains higher speeds and higher acceleration/deceleration rates than the FTP Cycle. Although not developed to specifically model the driving events which occur during start-up procedures, bag 1 of the UC represents a better account of today's driving habits.

The Start Correction Factor will also adjust the basic emission rate to model start emissions which are independent of running emissions by focusing strictly on the emissions produced by the start-up procedure. This is accomplished by incorporating the cumulative emissions produced in the first 100 seconds of UC bag 1 as shown in equation (3).

Table 5 contains the Start Correction Factors that are applied to the basic emission rate of bag 1 of the FTP.

Table 5. Start Correction Factors

	Non-Catalyst	Catalyst-equipped *
HC	1.3124	2.1651
CO	1.0704	1.7976
NOx	0.1528	1.4059
CO_2	0.5302	0.5452

* Catalyst-equipped also represents the EHC vehicle.

COMPARISON OF CURRENT AND PROPOSED METHODS

As explained earlier, currently in EMFAC, cold and hot start emissions in grams per trip are calculated as two sets of numbers using bags 1, 2 and 3 of the FTP. To quantify total start emissions in grams per day, the total number of trips per day are weighted by 0.53 and 0.47 fractions for cold and hot trips, respectively.

In the proposed methodology, a trip profile consisting of the number of trips by various soak times (time interval between consecutive engine-off and engine-on) per day was needed. This information was obtained from the ARB's study entitled "Monitoring of Personal Driving Habits and Vehicle Activity". In this study, vehicles instrumented with dataloggers were given to randomly selected participants in exchange for their personal vehicles. The real-time information on personal driving habits and vehicle utilization of drivers on the road obtained through this study was used to quantify the differences in the start methodologies. Data obtained from two instrumented vehicle exchanges were analyzed to obtain the trip profile shown in Table 6. One vehicle collected one week, and the other vehicle two weeks worth of trip activity data.

In the new methodology, start emissions after each soak ranging from 5 minutes to 12 hours were calculated separately, weighted according to the trip profile, and then added together to obtain total start emissions in grams per trip. In order to compare the effect of the proposed methodology with the current methodology on an equal basis, the trip profile used in the proposed methodology was used to obtain revised cold and hot start trip fractions per the EMFAC definition. These revised fractions were 0.42 and 0.58 for cold and hot trips respectively.

Table 6. Trip Profile of a Typical Day

Soak Time (minutes)	Current methodology Cold or hot start	Proposed methodology Fraction of soak
Overnight	Cold	0.09
660	Cold	0.02
600	Cold	0.01
540	Cold	0.01
480	Cold	0.01
420	Cold	0.01
360	Cold	0.02
300	Cold	0.02
240	Cold	0.03
180	Cold	0.06
120	Cold	0.11
60	Cold	0.03
50	Hot	0.04
40	Hot	0.05
30	Hot	0.07
20	Hot	0.11
10	Hot	0.32
5	Hot	0.00
Total		1

Equations and Sample Calculations

To illustrate the impact of the new methodology on estimating start emissions, sample calculations for catalyst-equipped HC emissions have been performed using both methods.

<u>Current Methodology (EMFAC 7F)</u>
For the current methodology, the following equations are used to calculate total start emissions in grams per trip for HC, CO, NOx, and CO_2:

$$CI = (Bag1 - Bag2 * SCF) * 3.59 \tag{4}$$
$$HI = (Bag3 - Bag2 * SCF) * 3.59 \tag{5}$$
$$\text{Total start emissions (grams/trip)} = (CI * 0.42) + (HI * 0.58) \tag{6}$$

where
- CI is the cold start incremental or cold start emissions in grams per trip for an overnight soak. This represents start emissions for all soaks greater than or equal to 60 minutes for catalyst-equipped vehicles.
- HI is the hot start incremental or hot start emissions in grams per trip for a 10 minute soak. This represents start emissions for all soaks less than or equal to 60 minutes for catalyst-equipped vehicles.
- Bags 1, 2 and 3 are the cold start, stabilized and hot start emissions of the FTP in grams per mile.
- SCF is the speed correction factor used in EMFAC.
- 3.59 is the length of bag 1 of the FTP in miles/trip.
- 0.42 and 0.58 are the cold and hot start trip fractions based on the trip profile in table 6.

Using equations 4 through 6, and the average FTP emissions for catalyst-equipped vehicles from Table 7, the HC emissions are calculated as follows:

$$CI = (1.025 - 0.276 * 0.812) * 3.59 = 2.875 \text{ grams/trip (cold)}$$
$$HI = (0.344 - 0.276 * 0.812) * 3.59 = 0.430 \text{ grams/trip (hot)}$$
$$\text{Total start emissions (grams/trip)} = (2.875 * 0.42) + (0.430 * 0.58)$$
$$\text{HC start emissions} = 1.457 \text{ grams per trip}$$

where
- 1.025, 0.276 and 0.344 are average bag 1, 2, and 3 FTP emissions in grams per mile.
- 0.812 is the speed correction factor for HC at 25.6 miles per hour.

Table 7. Average FTP Emissions for Catalyst-equipped Vehicles

	Bag 1	Bag 2	Bag 3	Comp
HC	1.0250	0.2764	0.3443	0.4415
CO	10.5038	2.6693	4.0261	4.6656
NOx	0.7896	0.2944	0.5745	0.4716
CO2	414.1014	412.3558	356.8635	397.4879

New Methodology (EMFAC 7G)

For the proposed methodology, applying the correction factors to the basic emission rate allows the start to be expressed in grams rather than grams per mile.

$$BER_C = BER\ (g/mi) * StF\ (mi) \tag{7}$$

where BER_C = corrected emission rate (g/100 sec for the overnight soak),
BER = basic emission rate (g/mi),
StF = Start Correction Factor (mi).

The following equation is used to calculate total start emissions in grams per trip:

$$\text{Total Start Emissions per trip} = \sum_{i=1}^{720} BERc * TFi * SFi \tag{8}$$

where i = soak period ranging from 1 minute to 720 minutes,
BER_C = adjusted basic emission rate in grams per 100 sec of overnight soak,
TF_i = fraction of total trips following soak period i,
SF_i = soak factor, that is start emissions after soak i normalized by start emissions after the overnight soak.

Using the FTP bag 1 emission rate from Table 7, the correction factor from Table 5, TF_i from Table 6, and SF_i calculated using equation 2 and the corresponding coefficients in table 4, the total start emissions per trip of HC is equal to 1.002 grams per trip. This results in a 31% difference in start emissions calculated by the new methodology over the current methodology in EMFAC. Table 8 compares the average start emissions for non-catalyst and catalyst-equipped vehicles using the current and proposed methodologies.

Table 8. Comparison of current (EMFAC 7F) and new (EMFAC 7G) methodologies

(a) Non-catalyst vehicles

	Current Methodology (g/trip/vehicle)	New Methodology (g/trip/vehicle)	% Difference
HC	4.89	3.63	-26
CO	23.12	28.50	23
NOx	3.15	0.95	-70
CO2	346.14	212.42	-39

(b) Catalyst-equipped vehicles

	Current Methodology (g/trip/vehicle)	New Methodology (g/trip/vehicle)	% Difference
HC	1.46	1.00	-31
CO	17.75	8.81	-50
NOx	1.60	0.88	-45
CO2	329.38	72.20	-78

IMPLEMENTATION OF LOW EMISSION VEHICLES

Low Emission Vehicle (LEV) regulations mandated by the state of California began in 1994 with the introduction of Transitional Low Emission Vehicles (TLEVs) for passenger cars and light-duty trucks. The LEV implementation schedule for passenger cars, light-duty trucks, and medium-duty trucks is given in Table 9. For modeling purposes in EMFAC, the catalyst-equipped vehicles tested for the starts test programs represent all catalyst-equipped vehicles including TLEVs for the three vehicle classes. The soak factors produced by the electrically heated catalyst equipped vehicle represent all LEVs and Ultra Low Emission Vehicles (ULEVs). The coefficients of the soak curves for catalyst-equipped vehicles and the EHC vehicle were weighted with the sales fractions for the different vehicle types of the respective model years to reflect this implementation. These model year coefficients are presented in Tables 10 and 11.

Table 9. Implementation Schedule for Low Emission Vehicles (LEV)

(a) Passenger cars

	0.39	0.25	TLEV	LEV	ULEV	ZEV
1997	0	0.73	0	0.25	0.02	0
1998	0	0.48	0	0.48	0.02	0.02
1999	0	0.23	0	0.73	0.02	0.02
2000	0	0	0	0.96	0.02	0.02
2001	0	0	0	0.9	0.05	0.05
2002	0	0	0	0.85	0.1	0.05
2003	0	0	0	0.75	0.15	0.1
2004	0	0	0	0.75	0.15	0.1
2005	0	0	0	0.75	0.15	0.1
2006	0	0	0	0.75	0.15	0.1
2007	0	0	0	0.75	0.15	0.1
2008	0	0	0	0.75	0.15	0.1
2009	0	0	0	0.75	0.15	0.1
2010	0	0	0	0.75	0.15	0.1

(b) Light-duty trucks

	0.39	0.25	TLEV	LEV	ULEV	ZEV
1997	0	0.73	0	0.25	0.02	0
1998	0	0.48	0	0.48	0.02	0.02
1999	0	0.23	0	0.73	0.02	0.02
2000	0	0	0	0.96	0.02	0.02
2001	0	0	0	0.9	0.05	0.05
2002	0	0	0	0.85	0.1	0.05
2003	0	0	0	0.75	0.15	0.1
2004	0	0	0	0.75	0.15	0.1
2005	0	0	0	0.75	0.15	0.1
2006	0	0	0	0.75	0.15	0.1
2007	0	0	0	0.75	0.15	0.1
2008	0	0	0	0.75	0.15	0.1
2009	0	0	0	0.75	0.15	0.1
2010	0	0	0	0.75	0.15	0.1

(c) Medium-duty trucks

	0.39	0.25	TLEV	LEV	ULEV	ZEV
1998	0	0.73	0	0.25	0.02	0
1999	0	0.48	0	0.5	0.02	0
2000	0	0.23	0	0.75	0.02	0
2001	0	0	0	0.95	0.05	0
2002	0	0	0	0.9	0.1	0
2003	0	0	0	0.85	0.15	0
2004	0	0	0	0.85	0.15	0
2005	0	0	0	0.85	0.15	0
2006	0	0	0	0.85	0.15	0
2007	0	0	0	0.85	0.15	0
2008	0	0	0	0.85	0.15	0
2009	0	0	0	0.85	0.15	0
2010	0	0	0	0.85	0.15	0

Table 10. Coefficients by Model Year for Passenger Cars and Light-duty Trucks

(a) HC

HC curve 1	a0	a1	a2	domain	HC curve 2	a0	a1	a2	domain
pre 1997	0	0.01272303	-6.2995E-05	0-89	pre 1997	0.57130263	0.00071965	-1.763E-07	90-720
1997	0	0.01052759	-4.3585E-05	0-107	1997	0.55378254	0.00071044	-1.287E-07	108-720
1998	0	0.00900792	-3.222E-05	0-129	1998	0.53819588	0.00070225	-8.64E-08	130-720
1999	0	0.00727147	-1.8569E-05	0-119	1999	0.5216425	0.00069354	-4.14E-08	120-720
post 1999	0	0.00560829	-5.0903E-06	0-117	post 1999	0.50641339	0.00068554		118-720

(b) CO

CO curve 1	a0	a1	a2	domain	CO curve 2	a0	a1	a2	domain
pre 1997	0	0.01194762	-4.7578E-05	0-116	pre 1997	0.70641161	0.0003344	1.001E-07	117-720
1997	0	0.01069029	-3.9169E-05	0-114	1997	0.63646041	0.00068085	-2.457E-07	115-720
1998	0	0.0095685	-3.1643E-05	0-114	1998	0.5742287	0.00098907	-5.533E-07	115-720
1999	0	0.00837714	-2.365E-05	0-113	1999	0.50813725	0.00131641	-0.00000088	114-720
post 1999	0	0.00707136	-1.3308E-05	0-107	post 1999	0.44733311	0.00161756	-1.1805E-06	108-720

(c) NOx

NOx curve 1	a0	a1	a2	domain	NOx curve 2	a0	a1	a2	domain
pre 1997	0.11796024	0.02966956	-0.00021496	0-61	pre 1997	1.12983289	2.2138E-05	-3.04E-07	62-720
1997	0.36965675	0.02263613	-0.00015843	0-71	1997	1.16978269	0.00023417	-6.83E-07	72-720
1998	0.60744429	0.01395902	-7.3702E-05	0-80	1998	1.23888887	0.0002248	-7.905E-07	81-720
1999	0.83760107	0.00863883	-3.902E-05	0-108	1999	1.29341685	0.00032613	-1.0338E-06	109-720
post 1999	1.05016953	0.00361983	-5.5745E-06	0-113	post 1999	1.37178406	0.00026788	-1.0892E-06	114-720

(d) CO2

CO2 curve 1	a0	a1	a2	domain	CO2 curve 2	a0	a1	a2	domain
pre 1997	0	0.00433672	-2.3932E-06	0-96	pre 1997	0.25889542	0.0014848	-6.364E-07	97-720
1997	0.0119785	0.00388711	-2.7569E-06	0-114	1997	0.27337235	0.00134171	-4.646E-07	115-720
1998	0.02569472	0.00298938	3.5276E-06	0-117	1998	0.28625167	0.00121442	-3.117E-07	118-720
1999	0.04026164	0.00203596	1.0202E-05	0-118	1999	0.29992979	0.00107922	-1.494E-07	119-720
post 1999	0.0537617	0.00114395	1.6526E-05	0-119	post 1999	0.31251366	0.00095484		120-720

Table 11. Coefficients by Model Year for Medium-duty Trucks

(a) HC

HC curve 1	a0	a1	a2	domain	HC curve 2	a0	a1	a2	domain
pre 1998	0	0.01272303	-6.2995E-05	0-89	pre 1998	0.57130263	0.00071965	-1.763E-07	90-720
1998	0	0.01064297	-4.5074E-05	0-110	1998	0.55378254	0.00071044	-1.287E-07	111-720
1999	0	0.00894124	-3.1696E-05	0-129	1999	0.53756023	0.00070191	-8.46E-08	130-720
2000	0	0.00723952	-1.8317E-05	0-119	2000	0.52133792	0.00069338	-4.05E-08	120-720
post 2000	0	0.00560829	-5.0903E-06	0-117	post 2000	0.50641339	0.00068554		118-720

(b) CO

CO curve 1	a0	a1	a2	domain	CO curve 2	a0	a1	a2	domain
pre 1998	0	0.01194762	-4.7578E-05	0-116	pre 1998	0.70641161	0.0003344	1.001E-07	117-720
1998	0	0.01069029	-3.9169E-05	0-114	1998	0.63646041	0.00068085	-2.457E-07	115-720
1999	0	0.00952275	-3.1336E-05	0-113	1999	0.57169079	0.00100164	-5.658E-07	114-720
2000	0	0.00835522	-2.3503E-05	0-113	2000	0.50692117	0.00132243	-8.86E-07	114-720
post 2000	0	0.00707136	-1.3308E-05	0-107	post 2000	0.44733311	0.00161756	-1.1805E-06	108-720

(c) NOx

NOx curve 1	a0	a1	a2	domain	NOx curve 2	a0	a1	a2	domain
pre 1998	0.11796024	0.02966956	-0.00021496	0-61	pre 1998	1.12983289	2.2138E-05	-3.04E-07	62-720
1998	0.36965675	0.02263613	-0.00015843	0-71	1998	1.16978269	0.00023417	-6.83E-07	72-720
1999	0.61628231	0.01375473	-0.00007237	0-85	1999	1.2556475	0.00014992	-7.123E-07	86-720
2000	0.84438601	0.00820735	-3.4722E-05	0-110	2000	1.31613529	0.00021136	-9.086E-07	111-720
post 2000	1.05016953	0.00361983	-5.5745E-06	0-113	post 2000	1.37178406	0.00026788	-1.0892E-06	114-720

(d) CO2

CO2 curve 1	a0	a1	a2	domain	CO2 curve 2	a0	a1	a2	domain
pre 1998	0	0.00433672	-2.3932E-06	0-96	pre 1998	0.25889542	0.0014848	-6.364E-07	97-720
1998	0.0119785	0.00388711	-2.7569E-06	0-114	1998	0.27337235	0.00134171	-4.646E-07	115-720
1999	0.02625409	0.00295277	3.7839E-06	0-117	1999	0.28677691	0.00120922	-3.055E-07	118-720
2000	0.04052967	0.00201842	1.0325E-05	0-118	2000	0.30018147	0.00107673	-1.464E-07	119-720
post 2000	0.0537617	0.00114395	1.6526E-05	0-119	post 2000	0.31251366	0.00095484		120-720

COMPARISON OF EMISSION FACTOR MODELS (EMFAC 7F vs. EMFAC 7G)

Using the methodology presented in this memorandum and the soak factors calculated for all model years, start emissions in tons per day were estimated in EMFAC 7G. Table 12 compares the estimated tons per day for HC, CO, and NOx using the old and new methodologies in EMFAC 7F and EMFAC 7G. These calculations are for catalyst-equipped vehicles in the South Coast Air Basin for calendar years 1990 and 2000. In order to accurately compare the two methodologies, the emissions estimates are calculated assuming the same trip distribution and number of starts. The resulting charts in Figure 9 illustrate that in general, the current methodology overestimates start emissions.

Table 12. Comparison of Calculated Start Emissions (tons/day)
EMFAC 7F vs. EMFAC 7G

(a) 1990

	7F	**7G**	**% Difference**
HC	97.67	60.49	-38
CO	1177.41	928.79	-21
NOx	101.66	112.54	11

(b) 2000

	7F	**7G**	**% Difference**
HC	69.01	64.07	-7
CO	870.21	660.61	-24
NOx	67.33	50.37	-25

CONCLUSIONS AND RECOMMENDATIONS

The analyses presented in this memorandum indicate that in general HC, CO, and NOx emissions due to start procedures for catalyst-equipped vehicles may be overestimated in EMFAC (Table 12). Emissions data obtained on catalyst-equipped vehicles after various engine-off times does not support the current definition of cold starts. Start emissions produced after soak times of greater than 60 minutes are not the same as those produced after the overnight soak. This suggests that even after these intervals of soak, the catalyst is not completely cold; instead, it is still partially efficient in reducing HC and CO emissions.

The analysis of non-catalyst equipped vehicles suggests that on a gram per trip basis, start emissions are overestimated for HC, NOx, and CO_2 and underestimated for CO (Table 8). More data is needed between soak times of 120 minutes and 720 minutes to investigate the current definitions of cold and hot-starts for non-catalyst vehicles.

In order to further improve modeling capabilities for estimating start emissions, future start emissions testing should be performed:

- for soak times between 120 and 720 minutes for non-catalyst vehicles
- on more vehicles, particularly those with carbureted fuel delivery systems
- at different ambient temperatures,
- on vehicles using reformulated gasoline.

The ARB currently has a research contract, entitled "Study to Redefine Cold and Hot-Start Emissions", that will address the above issues.

A starts cycle is being developed which will focus on the events occurring during start-up procedures, before the catalyst is fully efficient. A starts cycle which is representative of real-world driving events that occur immediately following the start of a vehicle would eliminate the need for the correction factors used in this memorandum. The application of these correction factors is strictly a transitional step between the current and proposed methodologies.

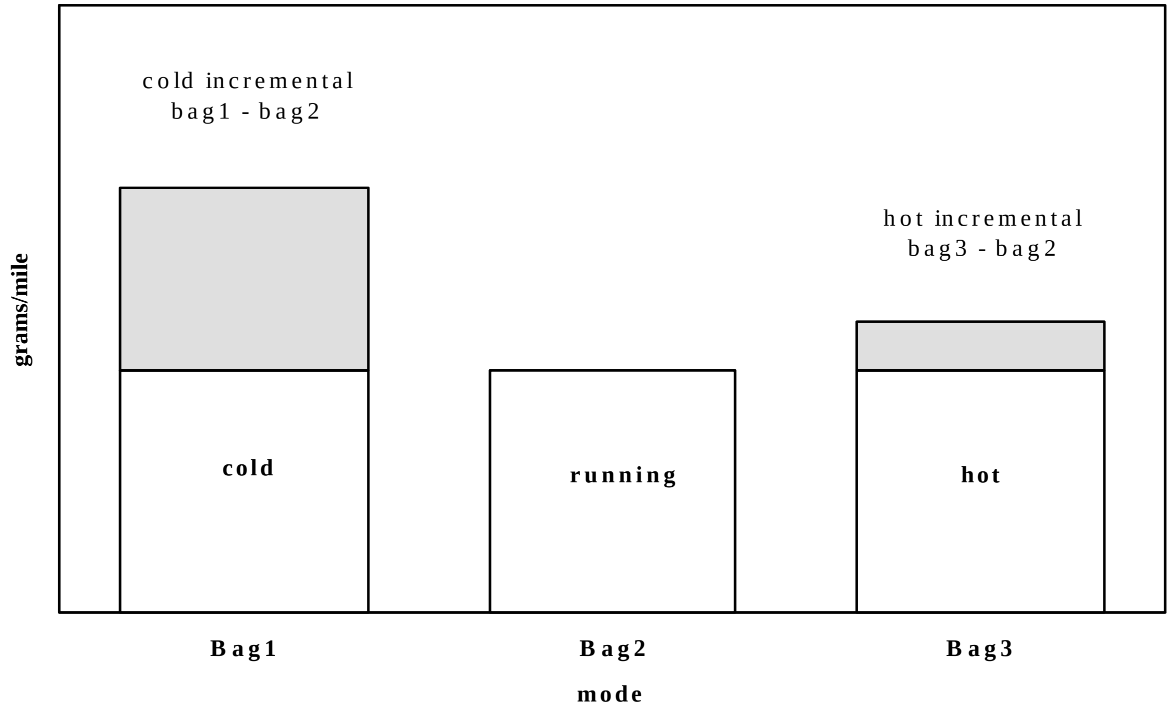


Figure 1. Incremental increases to running emissions.

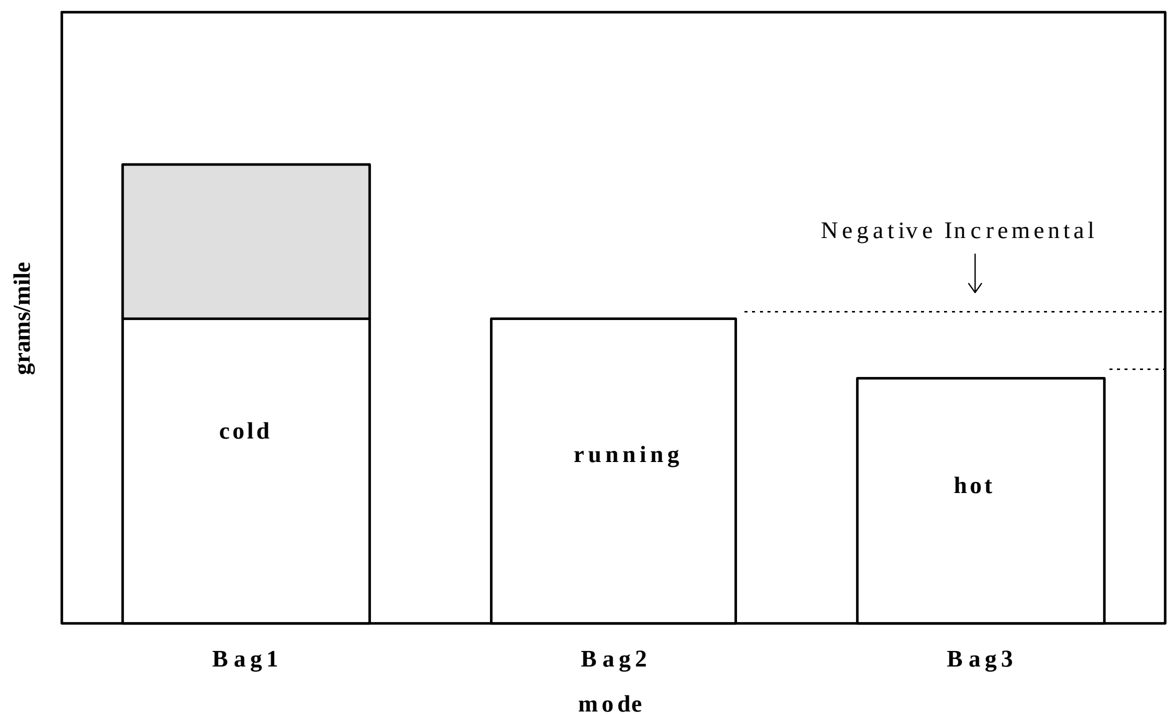


Figure 2. Negative incrementals occasionally produced by current methodology.

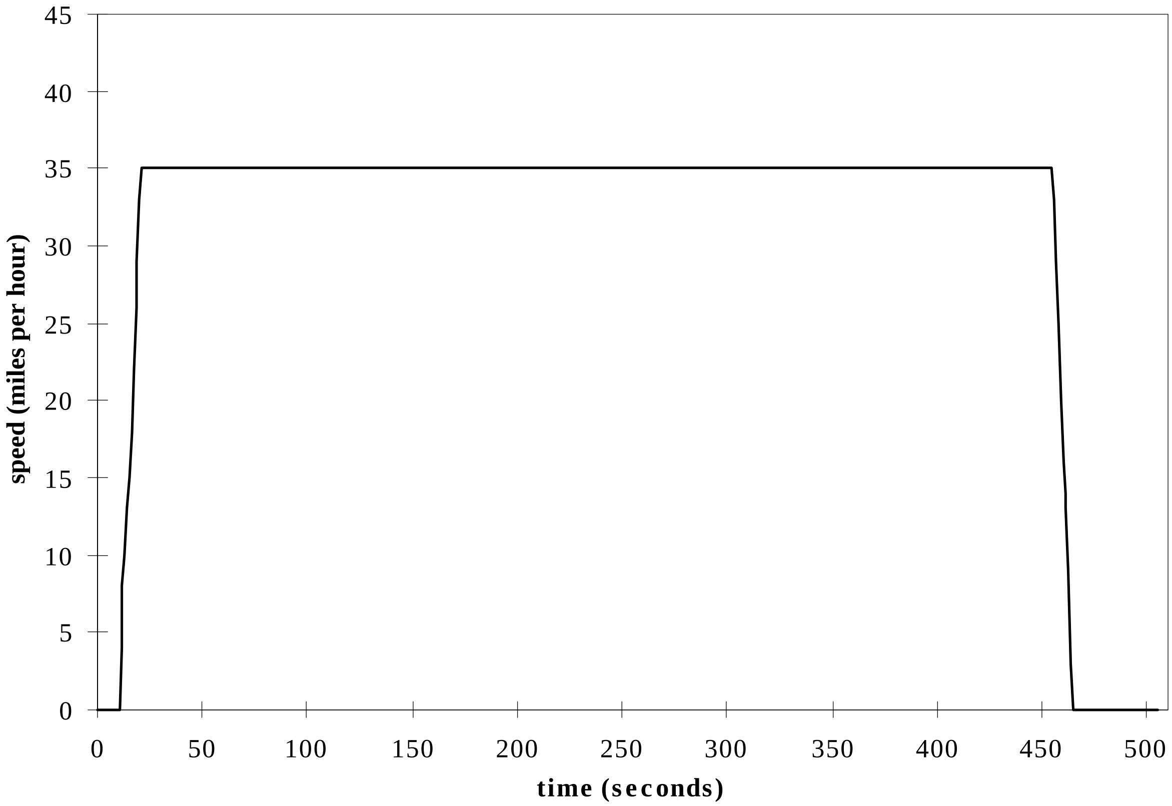
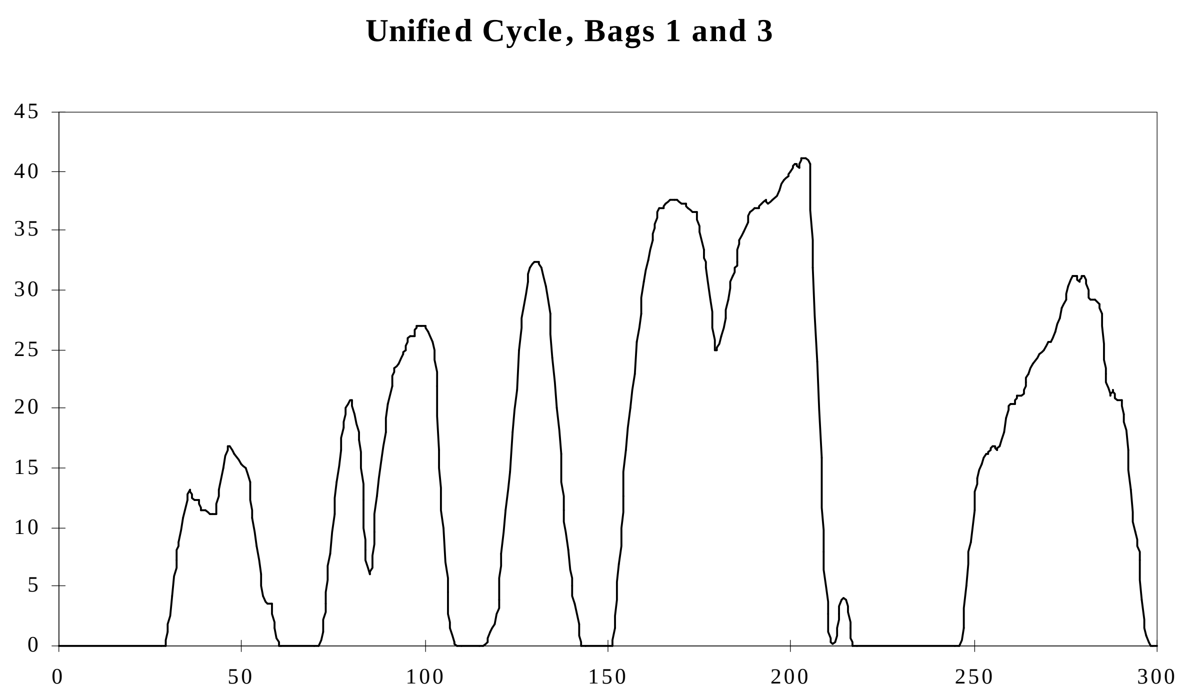


Figure 3. Speed vs. time trace of special start cycle.



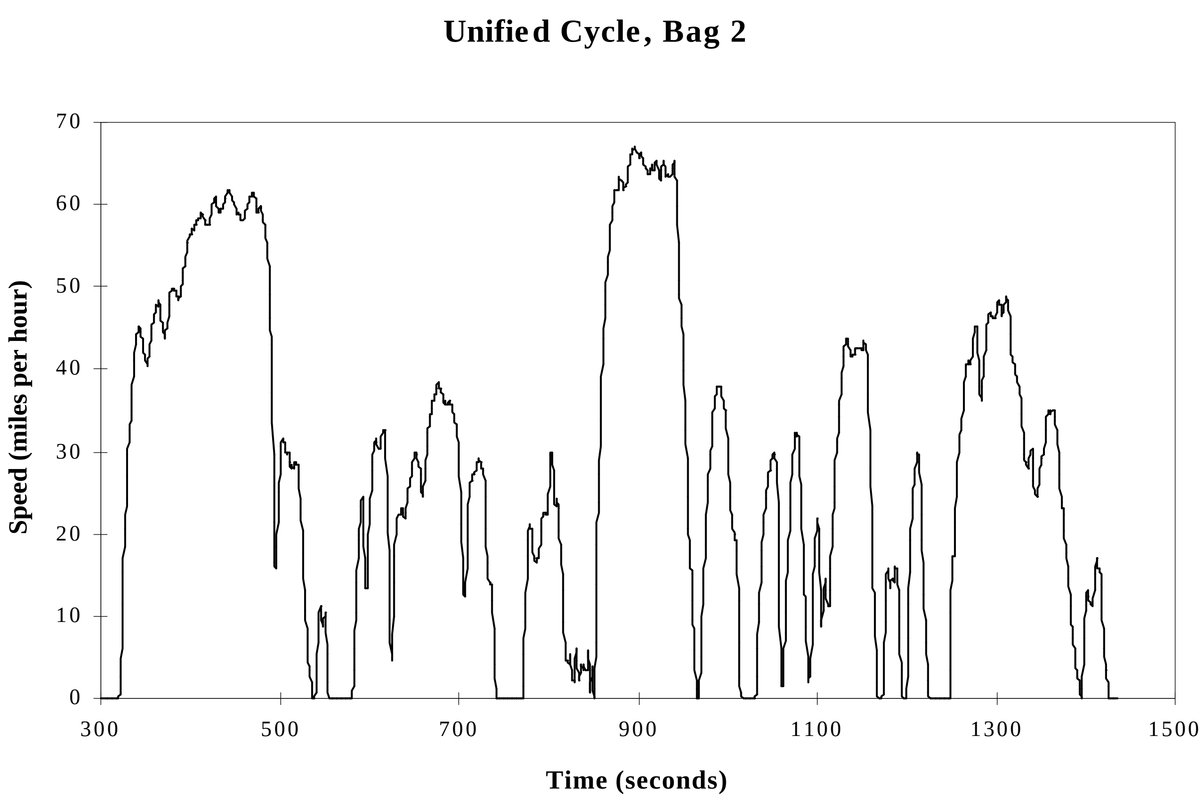


Figure 4. Speed vs. time trace of the Unified Cycle.

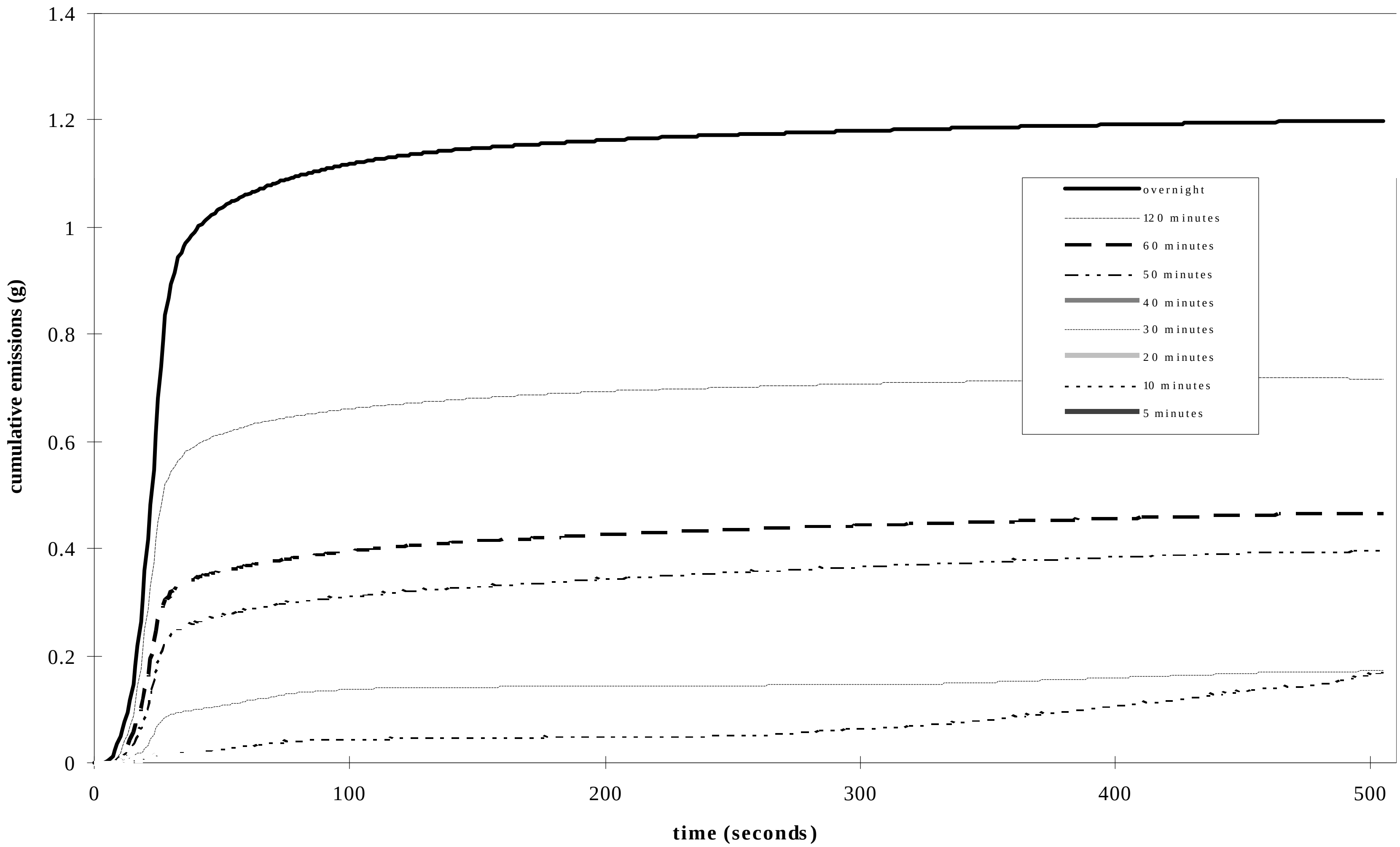
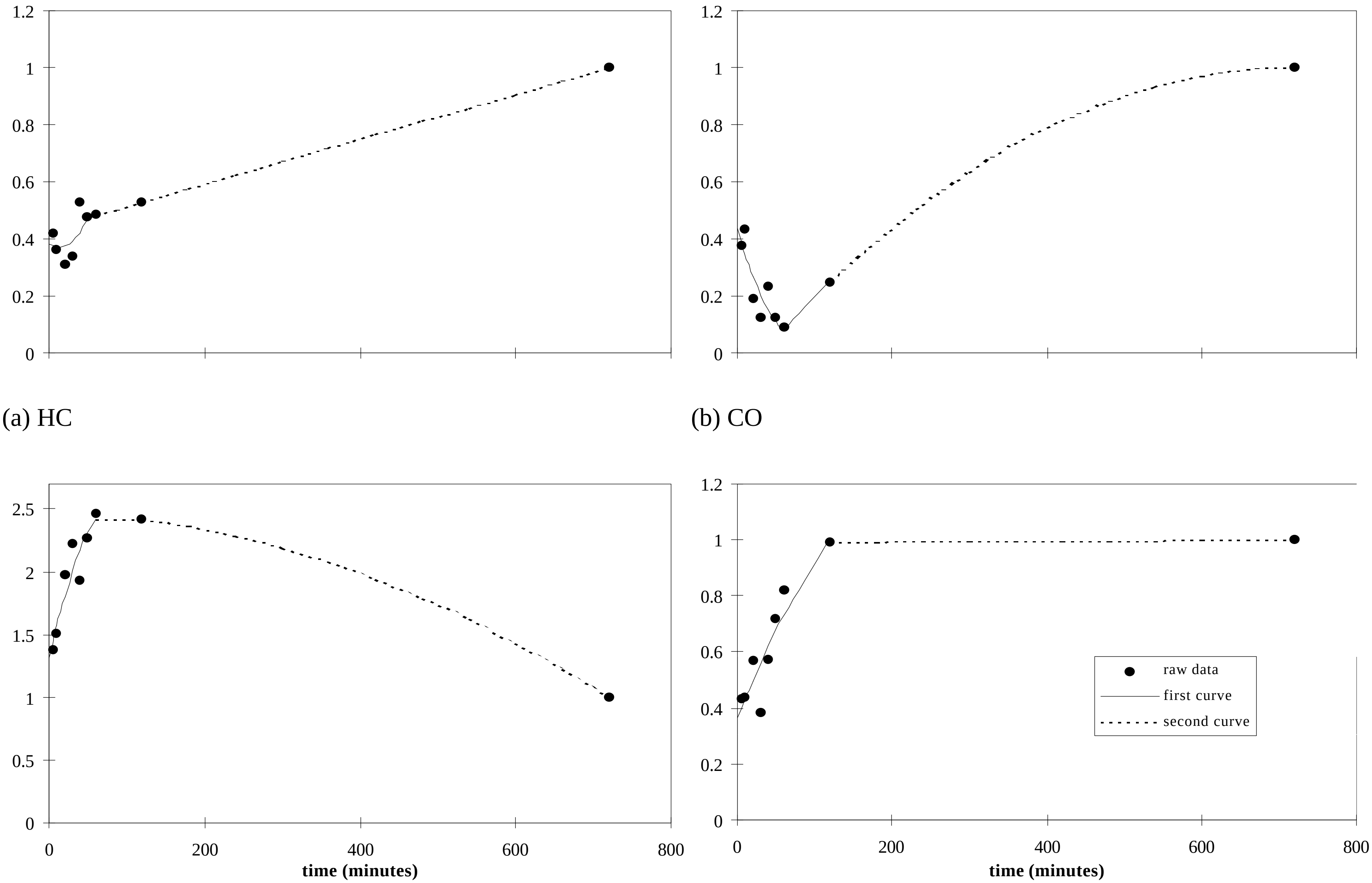


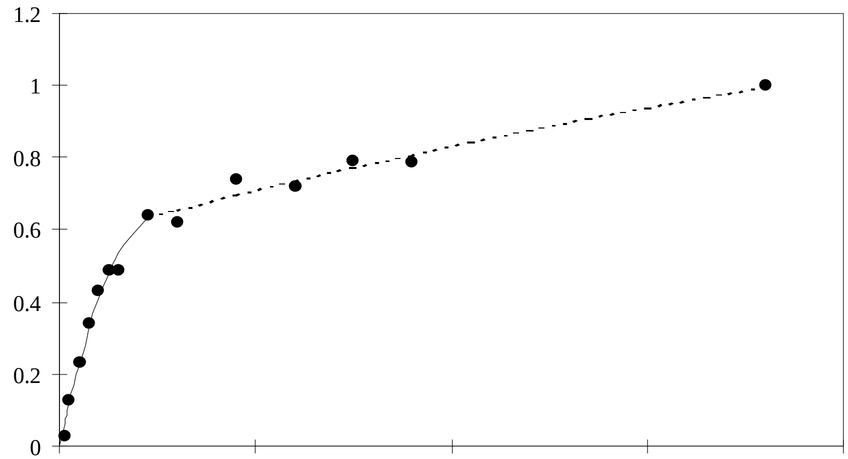
Figure 5. Vehicle 12, cumulative HC emissions for variable soak times.



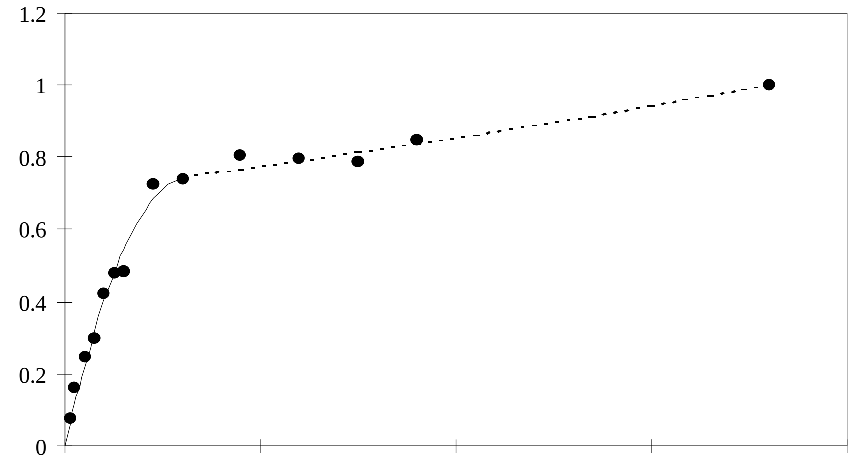
(a) HC (b) CO

(c) NOx (d) CO2

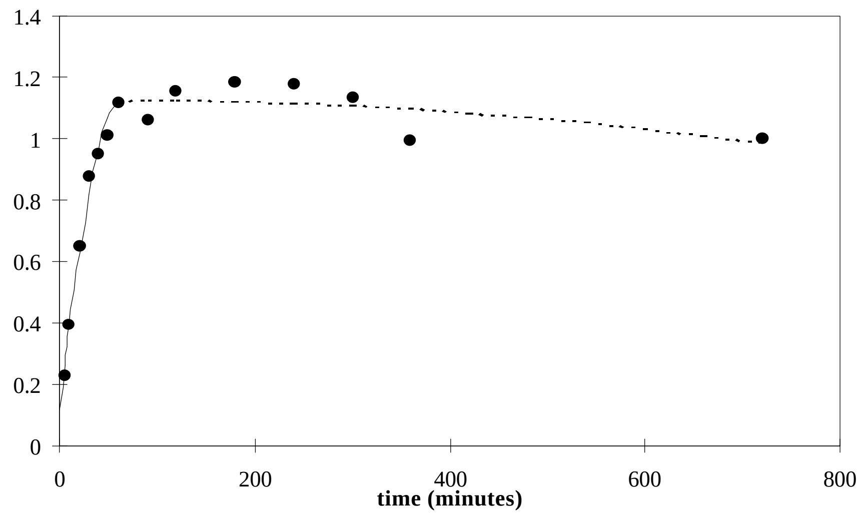
Figure 6. Normalized emissions for all non-catalyst equipped vehicles and the corresponding curve fits.



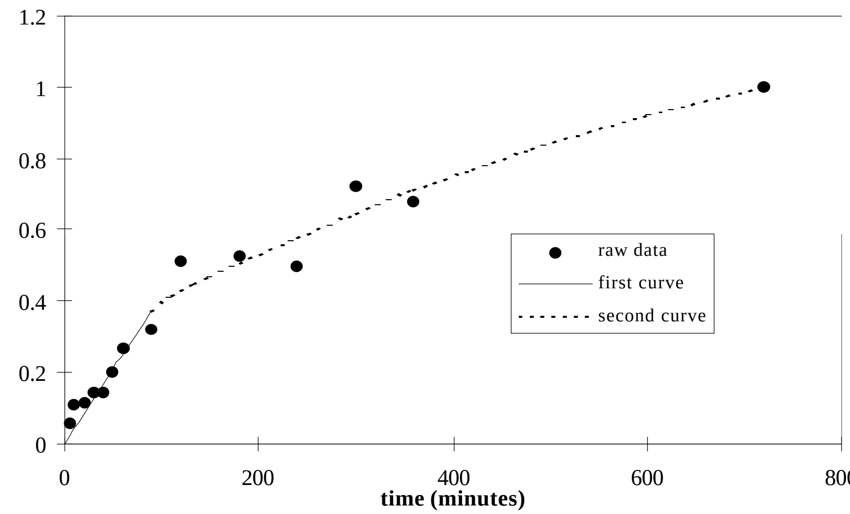
(a) HC



(b) CO

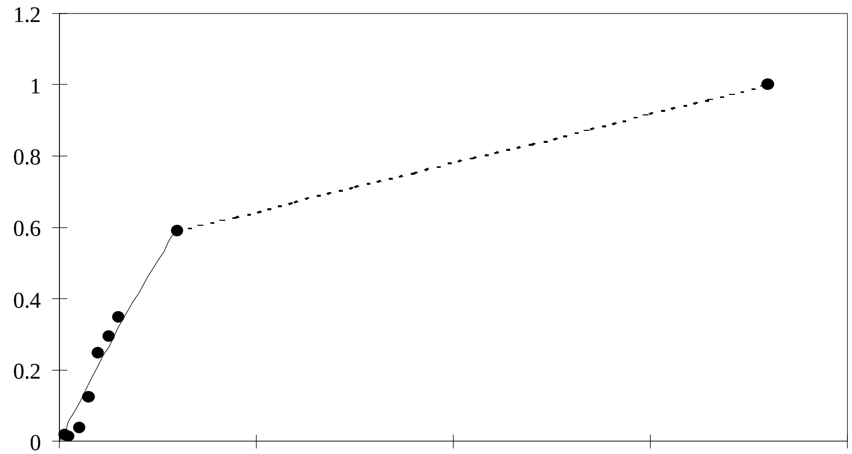


(c) NOx

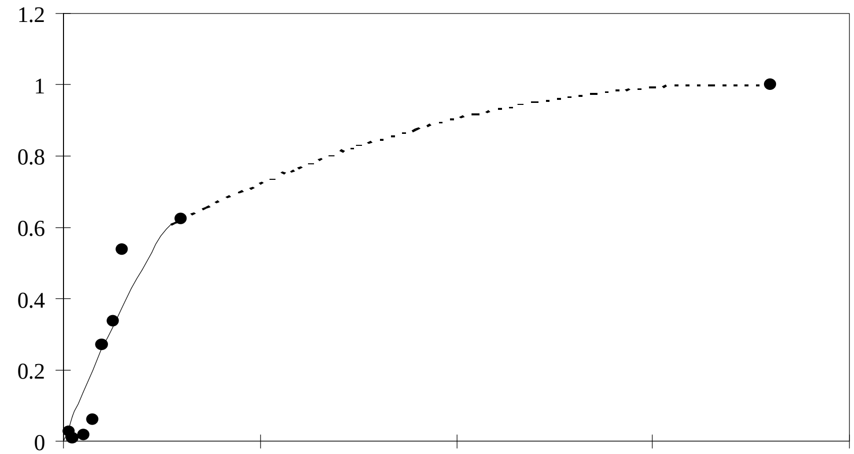


(d) CO2

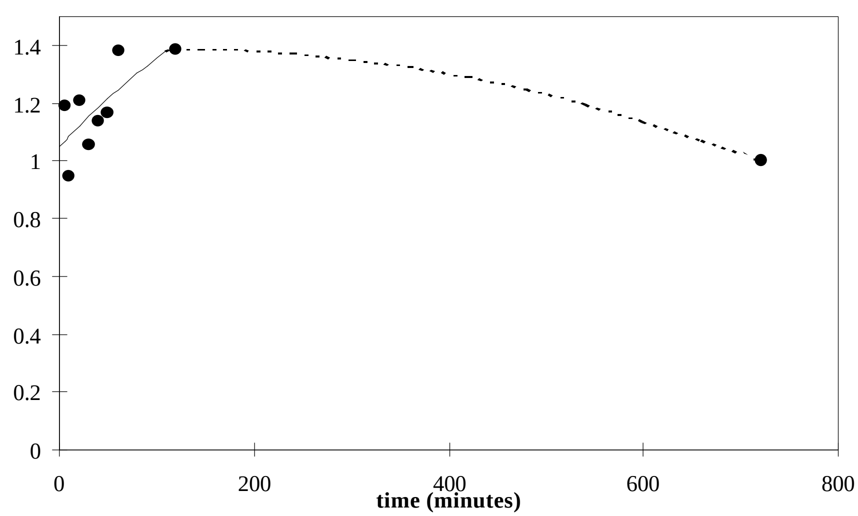
Figure 7. Normalized emissions for all catalyst-equipped vehicles and the corresponding curve fits.



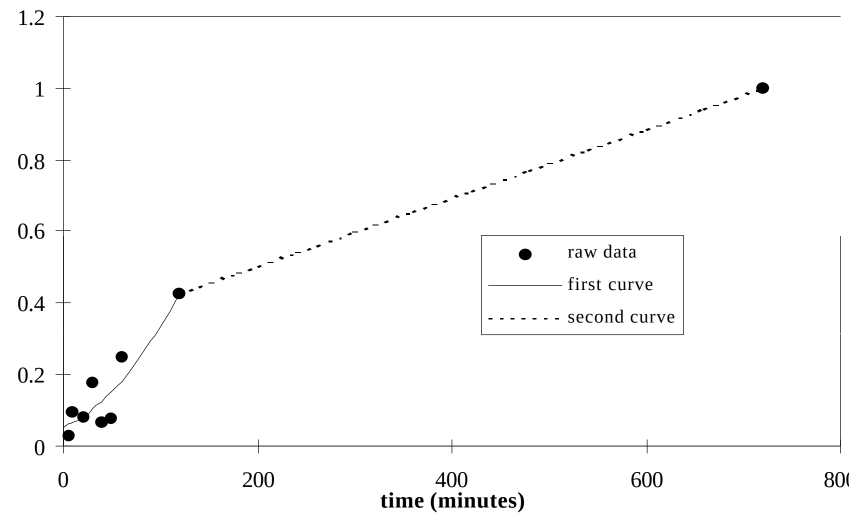
(a) HC



(b) CO

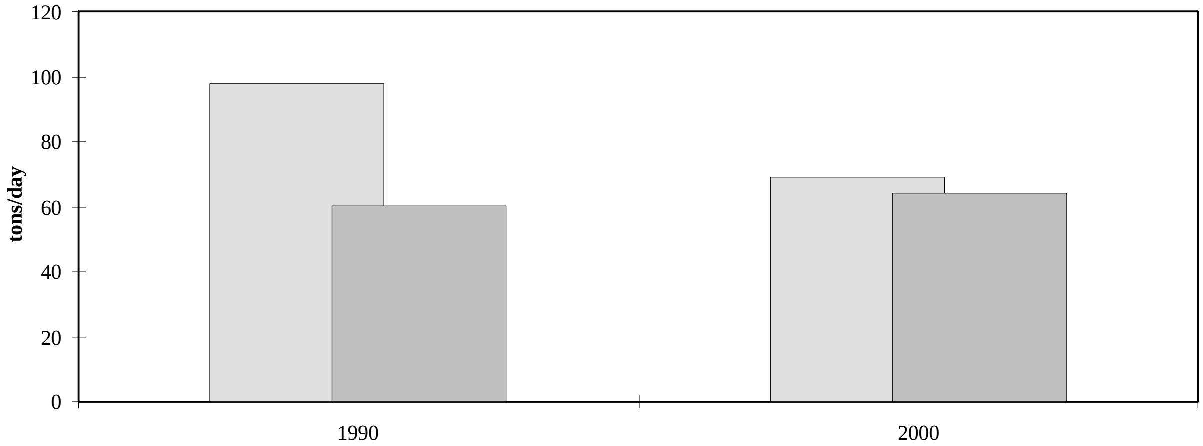


(c) NOx

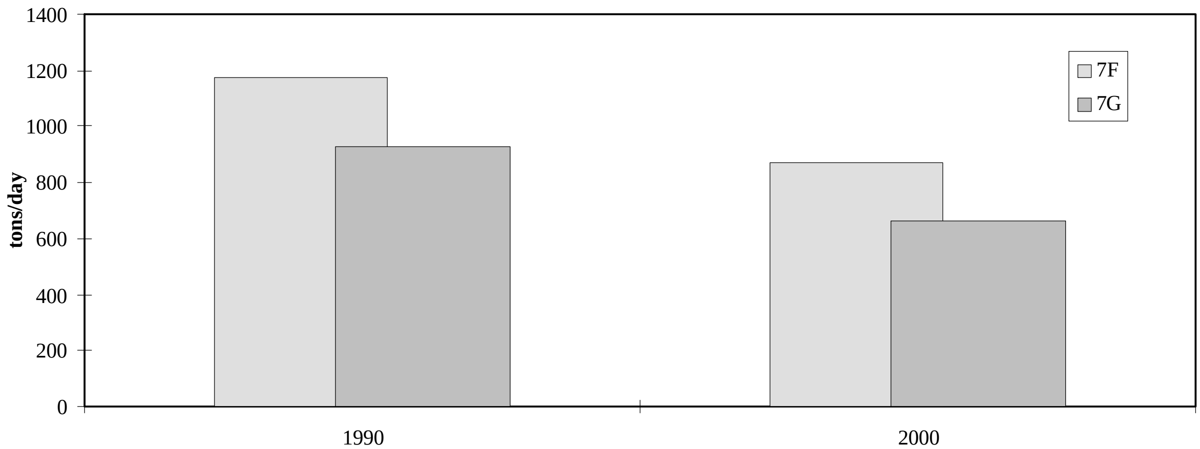


(d) CO2

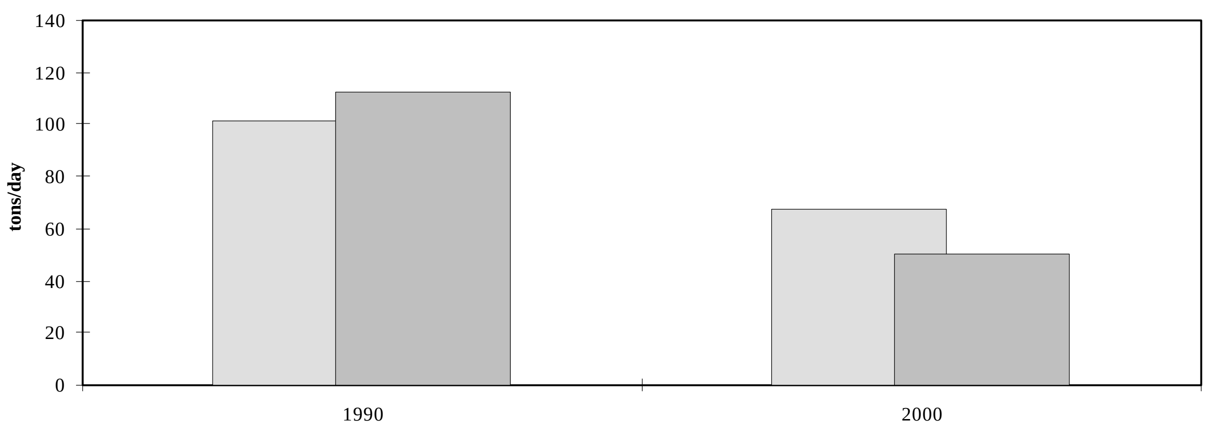
Figure 8. Normalized emissions for the EHC equipped vehicle and the corresponding curve fits.



(a) HC



(CO)



(c) NOx

Figure 9. Comparison of EMFAC 7F and EMFAC 7G inventory models for catalyst-equipped vehicles.